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EFFECT OF HEAT TREATMENT AND MECHANICAL CHARACTERIZATION OF AISI 4140 STEEL

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ABSTRACT

This work studies the outcome of heat treatment of AISI 4140 on wear, hardness, and tensile strength. The properties were compared after subject the specimen to annealing, normalizing, hardening and tempering. Amongst the methods used hardened specimen showed a hardness of RC45 and wear rate of near zero. Annealed specimen showed a Percentage Elongation of 15.56 and the tempered specimen had a tensile strength of 1109.4 N/mm ^{2}.

KEYWORDS: AISI4140 Steel, EN19 Steel, Heat Treatment, Tempering, Wear, Quenching & Tensile Properties

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Original Article

INTRODUCTION

Heat treatment is one of the methods to change the structure of the material thereby to get the desired properties. Annealing, normalizing, hardening and tempering are commonly used heat treatments to alter the microstructure and mechanical properties of materials particularly steels. Annealing is a kind of heat treatment used in order to soften iron or steel materials and refines its grains due to ferrite-pearlite microstructure; it is used where elongations and an appreciable level of tensile strength are required in materials. In normalizing, the material is heated to the austenitic temperature range and this is followed by air cooling. This is done to get pearlite structure which results into strength and hardness greater than as bought specimen. In hardening, the steel or its alloy is heated to a temperature high enough to promote the formation of austenite, held at that temperature for certain duration and then quenched in oil or water at a suitable rate. Tempering is done to impart ductility and toughness to the hardened specimen [1-3].

Heat treated AISI 4140 steel is used as the material for bolts, gears, spindles, couplings, sprockets, tool holders etc. [4-6].

As annealing temperature increases, strength properties of steelmaterial decrease whereas plastic properties rise. A substantial lowering of strength or hardness values occurs at temperatures which are close to 600 °C. [7] Hardness must be high to avoid plastic deformation. If tempering is done at 550^{0}C, higher hardness, tensile strength, yield strength, and ductility can be achieved for AISI H11 tool steel [8]. Hardened specimens shown greater tensile strength and hardness values with lesser ductility and impact strength when compared to other heat treated specimens. Hardening is recommended when the strength and hardness are the prime desired properties in the material. Water quenching resulted in higher tensile strength and hardness possibly due to the formation of martensite structure after quenching [9]. Medium carbon steel specimens quenched in palm oil during hardening

showed better ductility compared with that of water-quenched samples [10]. In the case of chromium nickel steel, annealed specimen shows the best result for microhardness test at 740^0C for a period of 60 minutes [11]. Dry sliding friction and wear properties of hybrid composites were improved by heat treatment [12]. Surface roughness and microstructure has been improved by heat treatment in die steels [13]. Annealing introduced coarse pearlitic microstructure and a microstructure having 10% spherical cementite with an increasing ferrite-pearlite banding in SAE 1050 steel. On the other hand, normalizing heat treatment increased ductility, hardness, impact energy with disappearing of banding but the life of the tool is reduced [14]. Martensitic phase transformation is used to increase the hardness of the steels [15]. Steel developed by hardening followed by tempering process at a required temperature contributed highest ultimate tensile strength with the best combination of ductility, impact strength and hardness which is essential for structural use. With the removal of brittleness, tempering results in good combination of toughness, ductility, hardness, and strength. To alter the microstructure and accordingly to change the properties of the steel, heat treatment processes are used. As tempering time and temperature increased, ultimate tensile strength gradually decreased whereas percentage elongation was increased [16-19]. Mild steel specimens showed better results for normalizing heat treatment process while stainless steel specimens responded better for annealing heat treatment process [20].

Table 1 Chemical Composition of the AISI 4140 Steel Used in this Study

Fe	C	Si	Mn	Cr	P	Mo	S
97.56%	0.38%	0.16%	0.8%	1.00%	0.035%	0.02%	0.04%

EXPERIMENTAL DETAILS

Specimen Preparation

The chemical composition of the material used for the present study is shown in Table 1. Standard specimens are prepared with the required dimensions for wear, hardness, and tensile tests. ASTM G-99, ASTM E18-02, and ASTM E8M cylindrical specimens are prepared for wear, hardness and tensile tests respectively by turning and polishing. Figures 1, 2 and 3 show the wear, hardness, and tensile specimens respectively.

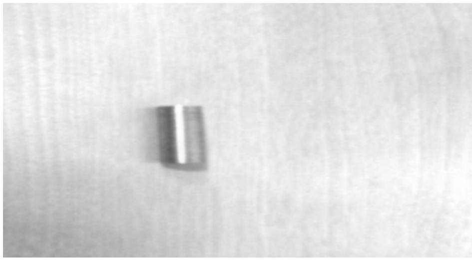

Figure 1: Specimen for Wear Test

Figure 2: Specimen for Hardness Test

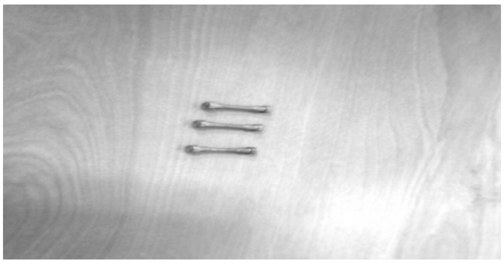

Figure 3: Specimen for Tensile Test

Heat Treatment Procedure

Specimens are heated to the austenitic state by using the Electric furnace. All specimens are prepared from as bought steel, subjected to four types of heat treatments such as annealing, normalizing, hardening, tempering and compared with as bought specimen. Five sets of specimens for five conditions are prepared. The set of specimens except set of tempering and as bought specimens are kept in the furnace and heated till the temperature reaches 900^0C. Then the furnace temperature is maintained at 900^0C for one hour to convert the room temperature structure into austenite.

For normalizing a set of the specimen is taken out and cooled in open air. For hardening, the specimens are taken out and rapidly quenched in oil. For annealing, the set of specimens are left to cool in the furnace itself.

For tempering the set of specimens are heated to 900^0C and maintained at that temperature for an hour then quenched rapidly in oil. Later it is again heated to 500^0C, held at that temperature for about 2hrs then taken out from the furnace and subjected to cool in air. Later all the specimens are cleaned by emery paper. Quechan used is SAE 30 oil.

Testing

The heat-treated specimens are further subjected to mechanical tests like wear (Pin on disc), hardness (Rockwell) and tensile test (Computer controlled tensometer). In wear test, the diameter of the wear track is 120mm, test duration is 15minutes and rpm of the disc is 800 for each specimen.

RESULTS AND DISCUSSIONS

Wear Test

Wear resistance of hardened specimen is very high compared to other treated specimens [Table 2]. Wear rate graph [Figure 4] shows almost ‘zero’ wear up to 15Km of sliding distance in the hardened specimen. Later there is a slight increase in the wear rate for further 2-3Km. This may be due to the fracturing of the martensitic phases (brittle). Once fractured phases separated, a new layer of metal maintains a constant zero wear for another13-15Km distance. Again the fracturing may take place to enhance the wear rate. This is the normal behavior of the untempered martensitic structure. A surprisingly annealed specimen has shown best wear resistance. This may be because of the formation of bigger hardened stable chromium carbide phases. The tempered specimen shows less wear resistance compared to hardened and annealed. This may be due to the relaxation of the martensitic structure. The normalized specimen shows the least resistance to wear. This may be due to the formation of more weight percentage of pearlite. Also, the cooling rate may not be slow enough to produce an optimum percentage of pro-eutectoid ferrite with chromium carbide. Insufficient chromium carbide percentage may be the reason to reduce the wear resistance in the normalized specimen.

Table 2: Cumulative Weight Loss of as Bought as well as Heat Treated Specimens of AISI 4140 steel

Wear track radius (mm) 60 Sliding Distance = πDN/1000 m/min N = 800rpm			Weight (g)		Time (min.)
			500		15
Sliding Distance (Km)	**As bought**	**Annealed**	**Normalized**	**Hardened**	**Tempered**
	Cumulative Weight Loss(gm)				
4.52	0.003	0.001	0.005	0	0.002
9.04	0.006	0.002	0.01	0	0.004
13.56	0.009	0.003	0.015	0	0.006
18.08	0.012	0.004	0.02	0.001	0.008
22.6	0.015	0.005	0.025	0.001	0.010

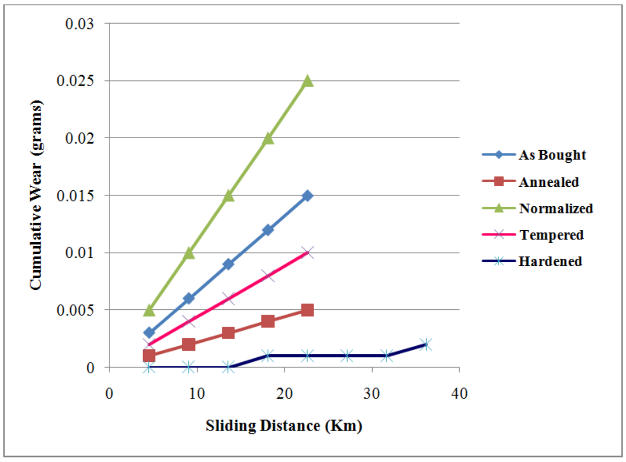

Figure 4: Wear Rate Comparison of as Bought as well as Heat Treated Specimens of AISI 4140 Steel

Hardness Test

A hardness of the annealed specimen is very less (R_C6) compared to other specimens [Table 3]. A decrease in hardness is due to the formation of coarser pearlitic particles with high interlamellar spacing. A high value of hardness (R_C45) is recorded for the hardened specimen. It shows the ability of the steel to form the martensitic structure. Martensite is supersaturated solid solution with body-centered tetrahedron unit cell. The carbon diffusion is not taking place when this phase is forming. As a result, the extra carbon is trapped in the martensitic structure. During tempering extra carbon present in martensite relaxes and hence diffusion of carbon is taking place. The decrease in hardness may be due to the decrease in ‘c’ to ‘a’ ratio of body centered tetrahedron martensite. As bought and normalized specimen show better hardness compares to annealed specimen [Figure 5]. Normalized specimen results from fine pearlitic phase with lesser interlamellar spacing. Finer phase with an increased weight percentage of pearlite is responsible to increase the hardness values. As bought specimen also show moderate higher hardness. This indicates that as bought specimen may be hot worked or as cast material.

Table 3: Rockwell Hardness Test Results of as Bought, as well as, Heat Treated Specimens of AISI 4140 Steel

Minor Load (Kg)		Major Load (Kg)		Indenter		
10		140		Diamond Cone		
Type of Heat Treatment	**Rockwell Hardness Number**					
Specimens	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Average**
As Bought	C24	C20	C20	C19	C25	C22
Annealed	C9	C5	C3	C6	C5	C6
Normalized	C31	C30	C29	C25	C26	C28
Hardened	C41	C45	C45	C48	C47	C45
Tempered	C24	C32	C34	C29	C28	C29

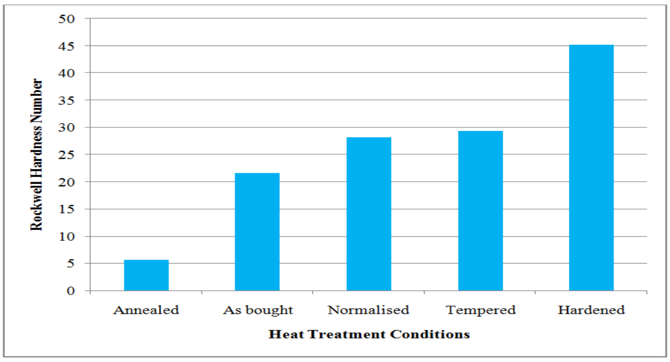

Figure 5: Rockwell Hardness Number Comparison of as Bought as well as Heat Treated Specimens of AISI 4140 Steel

Tensile Test

The load versus displacement diagrams of as bought and annealed specimens are of the same pattern. It indicates that the structures of as bought and annealed are almost similar. The strength values of an as bought specimen are higher than annealed [Table 4]. It shows that the ferrite and cementite particles are finer with lesser interlamellar spacing. The load versus displacement curves are plotted for all the tensile specimens. Normalized specimen behaves similarly to the hardened specimen with lesser strength values [Figure 6]. Both specimens behave purely brittle failure in tension. It also indicates that fine pearlite, which is obtained by normalizing is also brittle as that of the martensitic structure obtained by hardening. The tempered specimen shows an increase in ultimate tensile strength, it may be due to the transformation of retained austenite from the hardened specimen during tempering. Fig.7 indicates the increase in ductility of the specimen during tempering compare to hardening. Ductility of the normalized and hardened specimen remains same [Table 5]. It indicates that the martensitic and fine pearlitic structures of this steel are brittle in nature with variation in hardness values.

Table 4: Strength Values of as Bought, as well as, Heat Treated Specimens of AISI 4140 Steel

Type of Heat Treatment	Yield Strength (N/mm^2)	Ultimate Tensile Strength (N/mm^2)	Fracture Strength (N/mm^2)
As Bought	800.95	1025.6	764.65
Annealed	465.38	740.4	521.9
Normalized	830.2	830.2	830.2
Hardened	997.7	997.7	997.7
Tempered	1024.83	1109.4	876.9

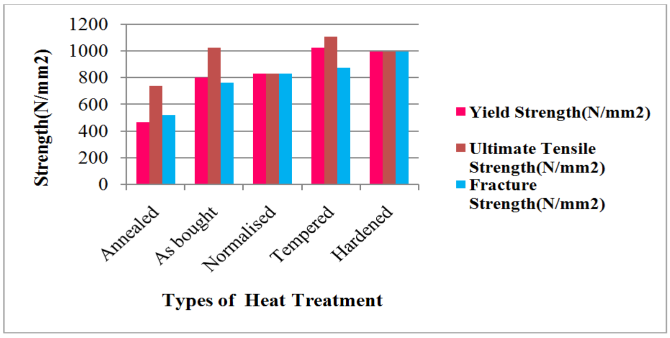

Figure 6: Strength Comparison of as Bought and Heat Treated Specimen of AISI 4140 Steel

Table 5: Ductility Results of as Bought as well as Heat Treated Specimens of AISI 4140 Steel

Type of Heat Treatment	Percentage Elongation	
	Peak Displacement	Break Displacement
As Bought	10.12	14.43
Annealed	10.43	15.56
Normalized	6.67	6.67
Hardened	6.67	6.67
Tempered	9.48	13.16

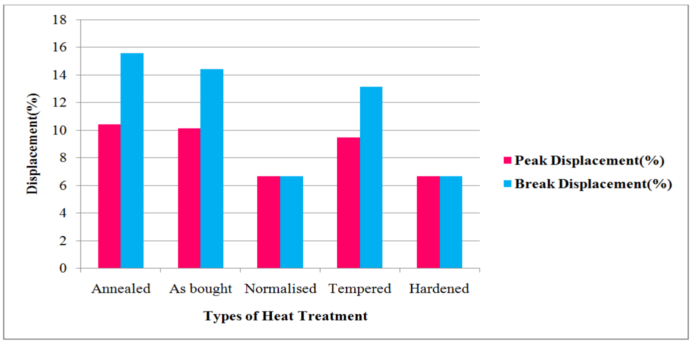

Figure 7: Ductility Comparison of as Bought and Heat Treated Specimens of AISI 4140 Steel

CONCLUSIONS

- The annealed specimen shows lower hardness and strength compared to as bought, hardened, normalized and tempered specimen.
- Hardness and strength indicate that pretreatment specimen is similar to the normalized specimen.
- Tempering improves the ultimate tensile strength of the hardened material.
- The tensile failure mode of the hardened and normalized specimens is purely
- -brittle in nature whereas annealed and as bought specimens, it is ductile.
- The normalized specimen also behaves like hardened specimen with a considerable decrease in strength values.
- A normalized specimen shows the least resistance to wear compare to hardening and other treatments. Even though normalized and hardened specimens are brittle there is a change in the wearing process.

- The hardened specimen shows highest wear resistance.

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